

1

AN OBSERVATIONAL PHILOSOPHY
FOR GEOS-C SATELLITE ALTIMETRY

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Since the GEOS-C altimetry experiment will be the first of a series of altimeter missions, its objectives should be defined within the context of the long-term objectives of satellite altimetry. One definition of these objectives was stated in the report of the 1969 Williamstown study on Solid Earth and Ocean Physics as the synoptic measurement of the topography of instantaneous mean sea level to an accuracy of 10 cm. In that report, emphasis was placed on determining variations of ocean topography over periods of time ranging from 2 cycles per day to 1 cycle per year with a spatial resolution of 1° (100 km) or better.

The need for establishing the accuracy and reliability of satellite-borne altimeter instruments is self-evident and clearly must be considered a primary GEOS-C objective. However, I would like to suggest that, although these factors are necessary, they are not sufficient for the future design of effective altimetry systems. An altimetry system is not only comprised of satellite instrumentation and data acquisition, but also of all elements of the data analysis functions, including computer software and physical models such as geopotential models, ocean current and density variation models, etc. To fully establish the feasibility of attaining a 10 cm system accuracy, and to provide the inputs needed for the design of efficient altimeter systems in the future, the GEOS-C altimetry experiment must include an extensive investigation of all the above-mentioned factors. This in turn implies that another primary objective of GEOS-C must be to acquire a substantial body of synoptic data to establish the ranges of values of the various oceanographic parameters that will be encountered in practice, to provide the actual experimental data necessary for developing and evaluating software and analytic procedures, and to determine just what ancillary data (e.g., the geopotential) we will need to acquire to reach the 10 cm accuracy level.

Having stated the broad objectives for the GEOS-C experiment, I will now outline what I consider to be the major problem areas in satellite altimetry, and briefly discuss their current status. I will then consider some design and operating questions relevant to the ability of the GEOS-C experiment to contribute to the stated long term altimetry objectives.

To make the subsequent discussion specific enough to provide useful information we must define some characteristics of the altimeter instrumentation. I will first assume that the GEOS-C and subsequent instruments will be pulsed radar altimeters operating in the X- to K-band region. At this time this choice is clearly the best from the standpoint of practical engineering considerations, since suitable components and systems are both available and in an advanced state of development, power requirements and antenna dimensions are consistent with satellite constraints, this region of the electromagnetic spectrum permits all-weather operation, and finally, ionospheric propagation errors are at a tolerable level.

With this type of system, the altimeter "footprint" on the ocean surface will be a circle with a diameter in the range 1 to 10 km. At wavelengths of 1 to 3 cm and for ocean-reflecting areas of square kilometers the radar echo received at the satellite will be the vector sum of the echos from a very large number ($>10^6$) of individual ocean-surface reflecting elements that will be distributed in range (height) over many (r.f.) wavelengths for all but an extraordinarily smooth ocean. The resulting distribution of relative phases among the individual echos will cause the amplitude to vary within each (return) pulse over a very great range. These amplitude variations, which will be distributed according to the Rayleigh probability density function, effectively prevent us from determining satellite-to-ocean altitude from any single pulse. Further, there is a minimum time (or distance travelled by the satellite) that must elapse between successive pulses to ensure the decorrelation of this Rayleigh noise that is necessary before a useful result can be obtained from the average of many pulses. For the case we are considering here, the minimum decorrelation time is of the order of 1 millisecond, and roughly some 1000 pulses must be averaged to obtain a reasonable altitude measurement.

Thus the output of the satellite altimeter will be a measurement roughly once per second of the vertical distance between the satellite and an elongated segment of ocean surface with dimensions of the order of 1 to 10 km perpendicular to the satellite subtrack and perhaps 10 to 20 km along the subtrack. The basic observational information from the altimeter will be a one-dimensional profile (averaged over the elongated footprint) of the ocean surface relative to the satellite orbit as it is traced out in time by the motion of the satellite. In addition, the roughness of the ocean surface will influence the shape and amplitude of the echo pulses, and may provide information on sea state.

Now, what are the problem areas? They are listed in table 1. First, there is the instrument per se, and its calibration. Although these are of primary importance, I will not discuss them further since they will be dealt with in detail by later speakers.

Table 1.

Satellite Altimeter Problem Areas.

INSTRUMENTATION

CALIBRATION

PROPAGATION

SATELLITE TRACKING

GEOID

SEA SURFACE EFFECTS

Since the altimeter measures the time interval for a pulse to travel from satellite to ocean and back, we must know the pulse propagation velocity to compute altitude. If we assume, as most everyone does in practice, that the light second is our primary length standard, we need only be concerned with departures from the vacuum velocity of propagation--viz., the influences of the ionosphere and troposphere on microwave propagation velocities.

For radio frequencies below 20 Ghz, the troposphere produces an apparent altitude change of about 2-1/2 meters. At any one ocean location, the variation of this altitude error with time will have a peak to peak amplitude of about 30 cm, and an RMS value of roughly 10 cm, these variations being the result primarily of variations in atmospheric water vapor content. There is a water vapor resonance line at 23 Ghz ($\lambda = 1.3$ cm) so that should be avoided. There are other molecular absorption lines for radio frequencies above 23 Ghz that will cause both large altitude errors and loss of signal (e.g. the oxygen line at 55 Ghz), so frequencies above 20 Ghz should be avoided. Although the troposphere will not be serious problem for GEOS-C, it is clear that corrections must be devised for a 10-cm system.

At the planned GEOS-C frequency of 13.9 Ghz, the uncorrected ionospheric range error will have a maximum of about 15 cm for daytime observations and about 3 cm at night. At 20 Ghz these errors would be halved. Even a rather crude correction can reduce ionospheric altitude errors to acceptable levels.

The satellite altitude must be known independently before the ocean profile can be gotten from the altimeter measurements. In the particular case of GEOS-C there will be no dearth of accurate tracking observations, since a substantial number of globally distributed ground stations will be available to use the onboard tracking instruments. Indeed, if all of the available systems are employed, GEOS-C will be the most intensively tracked satellite ever. GEOS-C will be tracked by laser ranging (12 or more stations with accuracies of 0.3 to 1 meter), TRANET radio doppler (perhaps 20 stations), C-band radar and the Goddard S-band Range and Range Rate System. As a result the accuracy of the computed GEOS-C orbits will be limited primarily by the accuracy of the gravity field model, and by the accuracy with which solar photon pressure and perhaps drag (depending on the GEOS-C orbital altitude) can be modeled.

The errors that would be introduced into the GEOS-C computed orbits by the best of the currently available gravity field models is in the range 3-10 meters. Improvements in the geopotential model which are in progress should reduce this uncertainty by a factor of 2 by the time GEOS-C is in orbit. (It should be noted that the GEOS-C tracking data should themselves lead to further refinement of the geopotential.)

Taken at face value, these orbital errors would present an unduly pessimistic impression. Actually, the orbit of a satellite at the altitudes now being considered for GEOS-C (perhaps 800 km or so) will be controlled almost entirely by the large scale features of the gravity field, i.e., those corresponding to spherical harmonics of degree and order 20 and lower, and the corresponding orbital perturbations of any significance will have frequencies of 100 per day or less. In other words, there should be no significant orbital perturbations for GEOS-C which have frequencies greater than 100 per day--or wavelengths shorter than about 5000 km. I would estimate that the altitude uncertainty for GEOS-C for wavelengths less than 5000 km will be less than one meter. Furthermore, the amplitudes of orbital perturbations decrease rapidly with decreasing wavelengths.

As a result, no serious problems should be encountered from GEOS-C altitude errors when the altimetry data are used to deduce topographic features with wavelengths less than 5000 km, which is the area of greatest interest.

Although the fine structure in the gravity field has little influence on the satellite orbit, its effect on the geoid is quite another matter. It will, of course, be necessary to separate the influences of the gravity field on ocean topography from those caused by oceanographic and meteorological phenomena. One important means

of effecting this separation will be to examine altimetry records taken at different times. Since time variations in the geoid are either extremely slow or have well defined frequencies (tides), it will be possible to extract from the altimeter data the time varying oceanographic factors. This approach will require substantial data sets obtained over the full operating life of the altimeter. A different method will be needed to identify the more stable oceanographic features. An independent determination of the geoid is obviously one means. Table 2 lists my estimates of the present errors in geoid topography for three somewhat arbitrary wavelength regions of the geoid. The estimates for the short and intermediate regions are quite uncertain because there are too little data. Indeed, GEOS-C will provide the first opportunity for obtaining a systematic survey of these geoid features over the oceans. A survey of this kind will be very useful in designing future altimetry experiments. Thus we have another reason for obtaining a thorough examination of all ocean areas accessible to GEOS-C.

Table 2.

Present uncertainties in the topography of the geoid.

Short wavelength	$\lambda < 200 \text{ km}$	10 to 20 meters peak.
Intermediate wavelength	$200 < \lambda < 2000$	10 meters
Long wavelength	$\lambda > 2000$	3-5 meters RMS

Improvements in the long wavelength region of the geoid will most probably be accomplished through dynamic analyses of satellite orbits. As noted above GEOS-C will be one of the satellites used for this purpose. An independent determination of the geoid in the intermediate region can also be obtained from satellite observations, either by direct integration of doppler observations of a minimum altitude satellite, or through an orbiting gravity gradiometer. The only satellite method appropriate for measuring the short wavelength geoid features is altimetry. An independent measure can only be obtained through surface observations such as shipboard gravimetry. One output of the GEOS-C observations which could be important to the design of future altimeter experiments would be a survey of these short wavelength features. This survey would indicate those regions where acquisition of surface data is most important. This information would be quite valuable, particularly in the light of the long times needed to carry out large scale surface observations.

Sea surface effects will not be discussed in any detail here, as they will be treated at length by subsequent speakers. Briefly there are two effects of interest. First the shape and amplitude of the reflected radar pulses are both expected to be influenced by sea state. This may enable us to obtain synoptic sea state information from satellite altimetry, if unique correlations can be deduced from comparisons of the altimetry data with "ground truth." The second effect is the altitude bias resulting from the difference between the electromagnetic and geometric centroids. This difference should not exceed 10% of the wave height. Since the median wave height for all of the oceans is of the order of 1.5 meters, the altitude bias should be acceptable for GEOS-C on an overall basis. However there will be many occasions, particularly during winter months at higher latitudes, when wave heights may be substantially higher. Thus it will be of considerable importance to monitor echo pulse shape and amplitude to identify sea state. It would then be possible to at least delete data when the altitude bias might be unacceptably large. There is also the possibility of being able to develop suitable corrections for this source of error.

The final point I wish to consider is the question of how much coverage--in terms of both geography and time--the GEOS-C experiment can provide. I consider this point basic to the ability of the GEOS-C experiment to establish the potential capability of satellite altimetry, to quantitatively delineate problem areas and to provide a sound basis for the design of subsequent altimetry missions.

Previous GEOS spacecraft have had three independent power systems: main, optical beacon and transponder. I would like to suggest that the

main and optical beacon supplies be rearranged to provide maximum power for the altimeter experiment. Table 3 lists the steady loads that these two supplies must support. The 0.2 duty cycle for the telemetry system will provide 5 hours per day of telemetry, which is generous. Table 4 shows the power budget for 20 sequences (140 flashes) for 2 lamps flashed simultaneously. Again this should be a generous allowance for this beacon.

Assuming the GEOS-C solar cell array to be the same as for GEOS-2, the total average power available at the battery terminals for the two power systems is 27.7 watts. The power available for the altimeters is thus $27.7 - 12.9 - 2.0 = 12.8$ Watts. The total energy per day for the altimeters is 307 Watt-hours.

It is presently planned to have two altimeter modes in GEOS-C: low power synoptic and high accuracy. Estimated power consumption is 40 Watts for the synoptic mode and 80 Watts for the high accuracy mode. If the available energy is divided equally between the two modes, we have the following duty cycle and total operating times for an 18-month operating life.

Mode	Hours/day	Total hours operation (18-month life)
Synoptic	3.84	2100
High Accuracy	1.92	1060

The speed of the satellite over the ground is about 240° per hour. If we assume that the narrow swath traced out by the altimeter footprint is an adequate sample for a path 1° wide, the altimeter sampling rate will be 240 square degrees of ocean per hour. The total coverage in 18 months under these assumptions will then be 506,000 and 253,000 square degrees for the synoptic and high accuracy modes respectively.

For an orbital inclination of 50° , the satellite will fly over some 75% of the total ocean surface, or 22,000 square degrees. For an inclination of 65° , the corresponding numbers will be 85% and 26,000 square degrees. Therefore, on an average, each square degree of ocean

Table 3.

Suggested steady loads for GEOS-C
main and altimeter power systems.

Doppler Beacon	5.5 Watts
Command System	1.0 Watts
Attitude Wheel	1.0 Watts
Telemetry System (0.2 Duty Cycle) avg power	1.2 Watts
Altimeter - continuous loads	
Delayed Command System	3.0 Watts
Data storage memory	1.0 Watts
Voltage-sensing cutoff switch	0.2 Watts
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Total steady loads	12.9 Watts

Table 4.

Optical beacon power budget for GEOS-C.

Optical beacon	600 Watt-Seconds per lamp-flash from battery
2 lamps	
7 flashes per sequence	
20 sequences per day	
Total energy per day	168,000 Watt-seconds
Average power consumption	2.0 Watts

covered by the satellite will be sampled with the following frequency in the synoptic mode:

Orbit inclination	Average number of samples
50°	23
65°	19

If we assume that the high accuracy mode will be concentrated on more limited "ground truth" areas totaling perhaps 500 square degrees of ocean, then some 500 samples will be obtained in 18 months from this more limited area.

The number of samples per square degree in each mode would seem to provide a quite satisfactory data base for the GEOS-C altimeter experiment.